Philosophy & Technology (2022) 35:30
https://doi.org/10.1007/s13347-022-00527-1

RESEARCH ARTICLE

Ethics of Nuclear Energy in Times of Climate Change: Escaping the Collective Action Problem

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Received: 29 August 2021 / Accepted: 18 March 2022

Abstract

In recent years, there has been an intense public debate about whether and, if so, to what extent investments in nuclear energy should be part of strategies to mitigate climate change. Here, we address this question from an ethical perspective, evaluating different strategies of energy system development in terms of three ethical criteria, which will differentially appeal to proponents of different normative ethical frameworks. Starting from a standard analysis of climate change as arising from an intergenerational collective action problem, we evaluate whether contributions from nuclear energy will, on expectation, increase the likelihood of successfully phasing out fossil fuels in time to avert dangerous global warming. For many socio-economic and geographic contexts, our review of the energy system modeling literature suggests the answer to this question is "yes." We conclude that, from the point of view of climate change mitigation, investments in nuclear energy as part of a broader energy portfolio will be ethically required to minimize the risks of decarbonization failure, and thus the tail risks of catastrophic global warming. Finally, using a sensitivity analysis, we consider which other aspects of nuclear energy deployment, apart from climate change, have the potential to overturn the ultimate ethical verdict on investments in nuclear energy. Out of several potential considerations (e.g., nuclear waste, accidents, safety), we suggest that its potential interplay — whether beneficial or adverse — with the proliferation of nuclear weapons is the most plausible candidate.

Keywords Nuclear energy · Climate change · Ethics · Decarbonization · Non-proliferation

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1 Introduction

In our era of climate change, decisions about energy use have become vexing moral questions. Societies that score high on measures of human development and well-being tend to consume high amounts of energy per capita, and the link seems at least partly causal (Gaye, 2007; Roy et al., 2015). Since most of this energy still comes from fossil fuels, there is a close correlation between economic development and greenhouse gas emissions, especially for developing countries. But, these greenhouse gas emissions cause climate change, which in turn leads to rising sea levels, disruption of weather patterns, increased droughts, and more extreme weather events. There is widespread agreement that this correlation must be broken: communities need to shift to emission-free energy sources and "decarbonize" their economies, without hampering human development and well-being.

Two fundamentally different types of technologies are prime candidates for replacing fossil fuels: those that harvest "natural" energy flows ("renewables") such as wind, water, solar, and geothermal energy, and those that rely on splitting atomic nuclei.[1] The latter are usually more controversial than the former. Some experts and broad swaths of the general public regard nuclear energy as unethical because of risks and/or sustainability concerns (Verbruggen et al., 2014). The contributions to the anthology "Ethics of Nuclear Energy" (Taebi & Roeser, 2015) are almost uniformly critical of nuclear energy, and in Germany, the accelerated phaseout of nuclear energy in the aftermath of the Fukushima accident in 2011 was recommended by an "ethics commission" (Ethik-Kommission, 2011).

In this article, we start with the working hypothesis that the interaction with climate change mitigation is the most important factor in the ethical assessment of nuclear energy use. This is what we set out to do in Section 2, 3, 4, 5 and 6. Our assessment is premised upon an assumption that we call "Substitutes must be cheap" (SMC). According to SMC, the chance of a successful global phaseout of greenhouse gas emissions will increase as the costs of clean substitutes fall. This premise is based on the analysis of climate change as arising from an intergenerational collective action problem (Gardiner, 2011), reviewed in Section 2. In Section 3, we present an ethical framework for assessing strategies of energy system development in terms of ethical criteria that may differentially appeal to proponents of different ethical frameworks. Next, in Section 4, we review economic challenges to decarbonization with and without nuclear energy, and in Section 5, we consider non-economic challenges. In Section 6, we conclude that, based on the considerations developed up to that point, investments into nuclear energy are ethically mandated in certain contexts.

Subsequently, in Section 7, we undertake a sensitivity analysis of that assessment, taking into account other factors besides climate change mitigation. We find that considerations of nuclear accidents and waste management do not in general revert

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[1] Nuclear fusion will likely not be commercially available at the time scales most relevant to climate change mitigation, which is why we focus on nuclear fission here. However, much of our discussion carries over to fusion if/when it becomes available

the overall verdict, whereas proliferation of nuclear weapons does have the potential to do so. Section 8 offers a brief conclusion.

2 The Moral Dilemma of Climate Change

Our discussion is broadly based on Stephen Gardiner's analysis of climate change as a "perfect moral storm" (Gardiner, 2011).

First, climate change reflects a collective action problem. On the one hand, fossil fuels individually benefit people by providing relatively cheap, abundant, and versatile energy access. Indeed, fossil fuels have historically contributed to, on aggregate, longer, healthier and by most measures "better" lives (Stern & Kander, 2012; Wrigley, 2013). In the wake of the industrial revolution, whenever and wherever it happened, dramatic and unprecedented increases in life expectancy and many other development indicators emerged (affluence, hygiene, education, women's rights, reduced child mortality). Fossil fuels are comparatively cheap and easily stored, can be used on demand, have a high energy density, and are easy to transport.

However, fossil fuel use also carries significant costs, which are borne by large groups of people, present and future inhabitants of the planet, including those who hardly participate in fossil fuel burning. In the case of the particle pollution resulting from combustion, as well as the extraction and transportation of fossil fuels, the costs are mostly localized, but as far as climate change is concerned, the costs are "socialized" on a global scale. There is thus a strong temptation for free-riding, with actors refusing to shoulder the burden of emission reductions while enjoying the benefits of others' reduction efforts.

Second, climate change poses an intergenerational conflict. Since the impact of CO_2 emissions is cumulative and present-day emissions will continue to have a warming impact hundreds of years into the future, there is a temptation for intergenerational buck passing: we emit now, they solve it later.

Third, there is the problem of institutional inadequacy: there simply is no international institution which is widely accepted as legitimate and could enforce collectively beneficial emissions reduction paths. Moreover, it is not in the short-term interest of the most powerful and polluting actors to create and support such international institutions.

As a result of these three factors, weaning humanity off fossil fuels is very difficult. The moral dilemma is particularly stark in the developing world. If emerging economies fail to get access to affordable and abundant energy, poverty risks being entrenched and key development indicators may stall or even worsen. Political actors have ethical responsibilities not only with regard to future generations, but also toward current generations, especially in developing nations.

We suspect that, even in rich countries, citizens will not be willing to abandon the familiar benefits from fossil fuels when no attractive substitutes are available.[2] While some private individuals are prepared to pay a premium for low-carbon products and services, escalating costs for many goods and services would erode democratic support for the policies (such as CO_2 taxes and green subsidies) that are necessary to bring down emissions. A further problem is that economic actors selling energy products and services compete with each other. As long as reliance on fossil fuels is the only option for remaining internationally competitive, many will either move to countries where fossil fuel use is still permitted or at least not penalized, or they will switch to emission-free substitutes but then end up being outcompeted by foreign companies that do not shoulder the burden of CO_2 taxes. This creates a dilemma for political actors: as long as they face serious trade-offs between decarbonization and economic flourishing, they are unlikely to enact legislation enforcing the necessary radical phaseout of emissions.

In the light of these considerations, we premise our analysis on the following assumption ("SMC" for "Substitutes must be cheap"):

> (SMC) To achieve decarbonization in a suitable time frame[3], energy policies have to secure the provision of all (or most) products and services in which fossil fuels are embedded at comparable or lower, and certainly not much higher, economic costs, including in countries where these services are not provided yet.

According to SMC, the chance of a global phaseout of greenhouse gas emissions will increase as the costs of clean substitutes fall. If substitutes are comparatively expensive, the willingness to pay a green premium may be restricted to rich countries or affluent consumers, preventing global decarbonization. Conversely, where substitutes are much cheaper than fossil fuels, they will "sell themselves" even without the need for carbon pricing, subsidies or other market interventions.

To be clear, SMC is a pragmatic principle and does not express an ethical judgment. It should not be interpreted as expressing a universal moral right to all the services and products currently provided by fossil fuels in developed countries; rather, it encapsulates the expectation that decarbonization will likely fail or proceed extremely slowly if the alternatives are more expensive, because people will resist the transition and refuse to give up fossil fuels. In other words, we believe that SMC is justified by the account of climate change as arising from a collective action problem: the larger the sacrifices demanded of current generations, and

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[2] Early signs of such a backlash are visible in industrialized nations, for instance with the "gilets jaunes" movement in France (protesting against diesel taxes) and with the growing discontent about increasing electricity costs for household consumers in Germany or California, both pioneers in the energy transition

[3] By "a suitable time frame," we mean no more than a few decades, in line with the analysis by the IPCC. The precise time frame depends on the assumed role of negative emissions technologies and the amount of warming considered tolerable given the compensating benefits of fossil fuels. For scenarios in which the 1.5- and 2-degree targets are fulfilled, emissions must fall precipitously rather soon and reach zero not much later than, preferably before, 2050 in most scenarios

especially of people in developing countries today, the lower the chances of solving the climate challenge.

To the extent that SMC is appropriate, economic considerations will be crucial for the ethical assessment of any energy technology, including nuclear energy, for climate change mitigation. Unlike, say, the majority of the contributions to (Taebi and Roeser 2015) the present investigation will therefore devote considerable space to the economic aspects of low-carbon energy systems, in Section 4. Conversely, one way of rejecting our conclusions (see Section 6 and Section 8) is by simply denying SMC.

3 Ethical Assessment Framework

Our analysis aims to be relevant in the light of different normative ethical frameworks such as (versions of) consequentialism, deontological ethics, virtue ethics, and contractualism. To this end, we consider nuclear energy in the light of three ethical criteria for evaluating courses of actions contemplated and taken by political actors with the power and responsibility to shape national and/or international energy systems. These criteria may differentially appeal to the proponents of different normative ethical frameworks, as we explain below.

The actors we have in mind are following specific "energy strategies," which one may think of as encompassing a set of guiding principles — e.g., energy security, economic affordability, the minimization of environmental impacts — and long-term goals — e.g., carbon neutrality by 2050 — but also including parameters such as energy market design and financing standards as well as subsidy and taxation schemes. Such a conception of "energy strategies" is evidently an idealization. Decision makers who jointly shape an energy system may not always act on coherent strategies, neither individually nor collectively. In practice, political and economic decisions concerning energy systems are often the result of compromises between different strategies, and may even be opportunistic, ill-motivated or ad hoc. As a result, strategies will almost never be implemented in pure form and outcomes will often reflect compromises, shortcomings in decision making and strategy switches. However, as will become clear in what follows, assessing the use of nuclear energy for climate change mitigation from an ethical angle is simply not possible without taking a broader perspective on energy system development.

The first two ethical criteria are most usefully regarded as appealing to a deontological ethical framework that includes a duty to, *ceteris paribus*, do no harm. Because of the close relationship between human development and access to energy outlined above, cutting off members of society from affordable energy access means causing harm. But emissions from energy generation, via contributing to climate change (and air pollution), also cause harm. Therefore, from deontological perspectives, an agent seems to be ethically compelled to reduce the emissions from her energy system as quickly as practically feasible and as long as it is compatible with her other duties. The first criterion we consider expresses this candidate duty:

- Criterion QUICK: An energy strategy must lead to the highest practically feasible near-term emission reductions for the actor's energy system, without causing significant harm elsewhere.

This criterion will be interesting to consider, but we do not endorse it ourselves because it has an important weakness: Steps that enable the highest practically possible near-term emissions may lock-in path dependencies and ultimately may make the complete phaseout of emissions more difficult. For example, in practice, the quickest routes to reducing emissions from a coal-based energy system will often involve the construction of new gas plants that provide on-demand electricity with lower emission intensity and can be built within a few years. But constructing such plants means constructing new carbon-emitting fossil-fuel infrastructure rather than zero-emission infrastructure. We suggest a second criterion to encode an actor's ethical duty to minimize the harm caused by emissions, which does not have that unwelcome consequence:

- Criterion ZERO: An energy strategy pursued by an actor must, with high chance of success, reduce the total greenhouse emissions of the actor's energy system to zero in a suitable time frame, without increasing emissions elsewhere.

To clarify: a "high chance of success" in the sense of ZERO means at most a small risk (say, expert probability assignment in the low single-digit percentage range) of encountering serious physical, social, political or other obstacles, which would prevent complete decarbonization within the envisaged time frame.

The first two criteria are concerned with an actor's duties to reduce her own emissions, and thus are most sensibly understood within a deontological framework. From a purely consequentialist perspective, the distinction between an actor's own emissions and those of others may appear less relevant. What ultimately matters are the total global emissions, and how one's own actions can affect them. We consider a consequentialist framework that *ceteris paribus* assigns lower utility to futures with overall higher greenhouse gas concentrations. Strategies with high expected utility will be ones that maximize the probability of fast global decarbonization and minimize the probability of decarbonization failure. From such a consequentialist perspective, effects of actions on the energy systems of *other* actors should also be taken into account, whether positively or negatively. For a consequentialist, it may even be acceptable to increase one's own emissions if that allows an actor to gain leverage over other actors' emissions, with overall lower emissions as a result. This motivates our third and last criterion:

- Criterion FACILITATE: An energy strategy must facilitate, rather than impede, the path toward global zero emissions, in a suitable time frame.

Some remarks on how our three criteria compare and are to be understood:

First, as we argued, the first two criteria have straightforward motivations within a deontological framework and the third within a consequentialist framework. They will also be of interest for a morally uncertain agent (MacAskill et al. 2020) who assigns non-zero credence to either of them. We suspect that proponents of other normative frameworks such as virtue-ethical and contractualist ones may also find them relevant, but we will not argue for this. We acknowledge that there may be normative ethical frameworks from the perspective of which other criteria of ethical energy system development are more salient.

Second, facilitating the path toward zero emissions for other actors in the sense of FACILITATE can occur along different routes, e.g., producing and exporting zero-emission fuels that other actors can use as plug-ins for fossil fuels (UNECE, 2021). Another route is investing in zero-carbon technologies that bring down the costs of these technologies globally and hence make emission reductions more economically attractive, thereby reducing the barriers to decarbonization highlighted by SMC.

Third, conforming to any of the three criteria is a matter of degree. For the sake of convenience, we will abbreviate "conforming to energy strategy X to a high (low) degree" by "(not) conforming to energy strategy X."

Fourth, and finally, degrees of conforming to the different criteria may positively correlate with each other, but trade-offs may also arise. On the one hand, conforming to ZERO may entail conforming to QUICK to some degree: any strategy that reliably leads to zero emissions will plausibly mandate significant near-term emission reductions. On the other hand, QUICK does not entail ZERO.

A trade-off can also occur between ZERO and FACILITATE. For example, if an island country's geography provides opportunities for constructing hydro dams, this may allow it to produce zero-emission domestic electricity. Iceland and New-Zealand are examples of such countries. However, with opportunities for further global deployment of hydropower being geographically limited, following this strategy may not yield significant spill-over effects that would facilitate decarbonization for multiple actors globally.

Conversely, a strategy that conforms to FACILITATE may not conform to ZERO or QUICK. For example, the generous subsidies for solar power deployment that Germany issued in the early 2000s have helped to dramatically bring down the costs of solar power for the rest of the world, by incentivizing the mass production of solar panels (Nemet, 2019). In light of SMC, the strategy pursued there seems to have been in line with FACILITATE. For Germany itself, however, given the comparatively high costs of solar energy at the time, this strategy conflicted with ZERO or QUICK.[4]

Understanding possible hurdles to establishing zero-carbon energy systems is key to assessing which energy strategies conform to ZERO and FACILITATE. We investigate economic challenges in Section 4 and non-economic challenges in Section 5.

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[4] The resources invested as subsidies, around 500 Euros per MWh according to the Erneuerbare Energien-Gesetz from 2000 (bit.ly/39sXyNf), could, in the near term, have averted more emissions when invested differently, but they may have been very efficient in the long term

4 Getting to Zero Emissions: Economic Challenges

According to SMC, for an energy strategy to conform to ZERO, the actual or perceived economic costs of energy must never become significantly higher than if unabated fossil fuel use were continued. Relatedly, if an energy strategy gives emitters economic incentives to move elsewhere where they can continue to emit, the strategy fails to conform to ZERO. And finally, in order to conform to ZERO, an energy strategy should not count on the import of emission-free energy from elsewhere unless there is a global abundance of exportable emission-free energy, an unrealistic scenario for the next few decades.

The greatest economic risks to energy strategies that aim for ZERO come from sectors/activities in which no candidate substitutes for fossil fuels have been deployed at scale and/or all are much more costly. According to Davis et al. (2018), these are the following: load-following electricity (12% of global emissions in 2014), iron and steel production (5%), cement production (4%), shipping (3%), aviation (2%), and long-distance road-transport (1%). Electricity production outside load-following electricity is an even bigger source of emissions (26%). Eliminating emissions from electricity at affordable costs is widely regarded as a key step in the decarbonization of other activities, including hard-to-decarbonize ones. The hope is that these will be electrified (e.g., short- and medium-distance road transport) or shifted to synthetic fuels, to be produced with emission-free electricity. For such synthetic fuels to have costs similar to those of fossil fuels, the emission-free electricity used to produce them will likely have to be cheaper than fossil fuel-based electricity.

4.1 Decarbonizing Electricity with Variable Renewables

Aspects of the economic costs of electricity sources are expressed in terms of their levelized cost of electricity (LCOE). This quantity specifies the required revenue from selling electricity to recover the capital investment of construction as well as maintenance, operating, and (where applicable) fuel costs. The most promising recent trends in the economics of emission-free electricity are cost reductions of solar and wind energy in the last few decades. The LCOE of both these sources have decreased rapidly due to learning effects in combination with economies of scale in the production of solar panels and wind turbines.

To be specific, according to the International Renewable Energy Agency (IRENA), median LCOE have fallen from 378 \$/MWh (in 2010) to 39 \$/MWh (in 2021) for solar PV and from 86 \$/MWH to 43 \$/MWh for onshore wind (IRENA, 2020, p. 14, Fig. S2). Significant reductions have also been achieved for offshore wind and concentrated solar power (CSP). Further reductions of these LCOE can be expected through learning and economies of scale. In many regions of the world, solar PV and onshore wind now undercut fossil fuel plants in terms of LCOE, sometimes even existing fossil fuel plants.

These promising developments notwithstanding, it would be premature to conclude that solar and wind energy are on the verge of making fossil fuels redundant as sources of electricity. The main challenge arises from an effect known as "value deflation" (Hirth, 2013; Sivaram, 2018), which occurs because the production profiles of solar power installations are highly positively autocorrelated (day/night and weather), and analogously for wind turbines. Electricity supply from these sources can be very high at specific times of favorable weather even while their average share of electricity production is still small. And it may vanish almost completely at other times, sometimes for several weeks, when wind speeds are low and there is a persistent cloud cover, or during the night.

As a consequence, if solar and wind energy already contribute a significant share to the overall electricity mix, further additions will predominantly deliver at times when supply is already strong. The economic value of such additions will be low in comparison with "flexible firm" sources, often fossil fuel-based ones, which can deliver at times of low wind and solar output, and which have to remain connected to the grid in order to supply reliable electricity. As a consequence, the overall costs of electricity provision will likely increase, potentially dramatically so, when high shares of solar and wind are being reached — even if these sources have a lower LCOE than other sources (NEA 2018; Loftus et al., 2015).

This value deflation can be studied in the German electricity system. According to an analysis by the Fraunhofer ISE for the year 2019, with wind and solar PV shares of 24.6% and 9.0% (Burger, 2020, p. 13), respectively, the average market values of these sources were reduced to 87.1% and 92.6% (p. 55) of the overall average market value of electricity. The marginal values of the newest additions are even lower. Conversely, the relative value of fossil fuel sources was increased, to 113.2% for fossil gas and 119.2% for hard coal. For the time being, wind and solar power are largely shielded against value deflation through fixed feed-in tariffs. The more these are needed, however, the higher the overall costs of electricity provision, in tension with ZERO, if SMC is assumed.

Another way to see why this is problematic is by recalling that, among all hard-to-decarbonize sectors/activities, load-following electricity is the single largest contributor. Expanding solar and wind energy effectively increases the need for load-following electricity, since fluctuations in demand are compounded with fluctuations in production.

Moreover, dispatchable energy sources such as fossil fuel plants are typically located close to centers of consumption (e.g., large cities) on relatively small industrial sites, which facilitates grid connection. By contrast, solar panels and wind turbines are often spread out over large areas and may be far removed from centers of consumption, in areas with suitable weather conditions (e.g., offshore wind). To bring renewable energy to centers of consumption, as well as to smooth out weather variations across large regions, the associated costs of grid infrastructure are far higher than for dispatchable sources such as fossil fuels or nuclear energy (Jenkins, Luke, & Thernstrom, 2018).

4.2 A Zero-Emission Grid with Mostly Variable Renewables?

Load-following electricity is produced by power plants that directly adjust their power output in response to fluctuating demand, which means that they will be often inactive or in waiting-mode. From an economic view, natural gas plants are well suited for this role, or, where available, coal plants or hydroelectricity. One major worry is that, in many cases, emission-free alternatives to fossil fuel plants will have far higher economic costs. By SMC, eliminating fossil fuel plants that provide load-following services from the grid will then become practically impossible.[5]

Various steps can be taken to prevent such an impasse. One, already noted above, is to build out electricity transmission and connect electric grids at scales that are large enough for weather correlation to be low or non-existent. Another partial solution is to provide incentives to customers for adjusting demand to production ("demand response"). Finally, electricity storage can be deployed to smooth out the non-alignment of production and demand. Batteries and, where geographically available, pumped hydro storage are among the prime options for short term storage of limited volume, though their use is economical only when sufficiently utilized — a few times per year is likely not enough. In the more distant future, longer term storage might be provided by "green" hydrogen (produced by solar and wind power through electrolysis), even though for now the conversion losses are substantial (efficiency in the range of 50–70% (IRENA, 2019) and long-distance transportation from renewable-rich areas entails further losses).

According to some energy system modelers, if these steps are taken in an intelligent way, a future electric grid relying far more on solar and wind power than today can be achieved without cost escalation. For instance, MacDonald et al. (2016) find that, by expanding solar and wind power, CO_2 emissions from US electricity can be reduced by 80% in 2050, compared to 1990 levels. Similarly, NREL (2012) concludes that renewables can reliably deliver 80% of US electricity by 2050 at costs comparable to today's. Both studies identify far bigger hurdles when trying to reach the goal of 100% renewables. Mechanisms giving rise to these hurdles are elucidated by Shaner et al. (2018) using a simple continent-sized toy model with historical hourly weather data. As these authors conclude, "to reliably meet 100% of total annual electricity demand, seasonal cycles and unpredictable weather events require several weeks' worth of energy storage and/or the installation of much more capacity of solar and wind power than is routinely necessary to meet peak demand" (Shaner et al., 2018, abstract).

Future cost developments in solar and wind power as well as electricity storage may render possible the complete decarbonization of US electricity, or even of the entire global energy system, by relying only on renewables, if trends of the last

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[5] Carbon Capture and Sequestration (CCS) has been proposed to neutralize the emissions of gas plants, but it makes those plants more capital intensive, lowers energy efficiency, and does not fully eliminate emissions. CCS may, however, prove to be the most attractive option for decarbonizing high-emission sectors such as cement and steel production (Friedman et al., 2019) and can help achieve "negative emission"

decade continue for several decades and global final energy does not change dramatically until the 2040s (Way et al., 2021). Potential realization pathways are indicated in (Jacobson et al., 2018; Ram et al., 2019; Teske & ed., 2019), based on optimistic assumptions about future costs. For instance, Ram et al. (2019) assume capital cost reductions for the cheapest solar PV technology from 1000 €/kW in 2015 to 246 €/kW in 2050 (p. 238) and for electrolyzers from 800 €/kW in 2015 to 248 €/kW in 2050 (p. 285).

A broader range of potential future cost developments is studied by Sepulveda et al. (2018). They find that, if the emission limit is lowered from 200 gCO_2/kWh down to 0 gCO_2/kWh and if only variable renewables are deployed, average electricity costs rise by a factor of 1.5 or 2 already in the lowest-cost projection, but by a factor of 3 to 4 in more cost-conservative projections. With such steep cost increases, emission-free electricity would fail to provide alternatives to fossil fuels via electrification in sectors that are hard to decarbonize. By SMC, this would lead to decarbonization failure.

This finding motivates investigating whether inclusion of nuclear energy in one's energy strategy may reduce the risk of cost escalation and thus facilitate decarbonization.

4.3 Economics of Nuclear Energy for Electricity Production

Nuclear energy starts out with an economic advantage over fossil fuels because, to produce a certain quantity of energy, little fuel is needed, in terms of volume or mass. In a standard light water reactor, which requires enriched uranium-235, fuel costs (including enrichment and conversion) amount to about 4 $/MWh, which is typically between two and five times lower than for coal or gas plants, even in the absence of a carbon price. Some nuclear fuel cycles do not require enriched uranium, and their fuel costs are lower still. Nuclear plants tend to have higher operation and maintenance costs than fossil fuel plants, but existing nuclear plants are typically cost competitive with (new, often also existing) fossil fuel plants in a variety of market condition, even in the absence of a carbon price and with the costs of decommissioning and waste disposal taken into account (IEA, 2019a).

The costs of nuclear energy are dominated by its capital costs. As the World Nuclear Association acknowledges: "In general the construction costs of nuclear power plants are significantly higher than for coal- or gas-fired plants because of the need to use special materials, and to incorporate sophisticated safety features and backup control equipment." (WNA, 2020) Incidentally, it is this need for specific safety features which has made nuclear energy impractical in road transport or aviation.

The capital costs of nuclear power plants consist of the "overnight" construction costs and the costs of financing during construction. The latter depend on interest charges and construction duration. Historically, where overnight construction costs have been in the range of 1000–3000 $/kW of installed capacity, financing costs were comparatively low, and construction durations in the range of 4 to 6 years, nuclear plants have been cost-competitive with fossil fuels plants. This applies to recently completed reactor build projects in China and South Korea (Lovering et al., 2016), and to many reactors built in Western countries in the 1960s, 1970s, and 1980s. France and Sweden provide examples of electric grids with very low carbon intensity (in the range 10–50g of CO_2 per kWh), in large part thanks to nuclear power. Reactors there were largely constructed in the 1970s and 1980s, at overnight costs mostly in the range between 1000 and 2000 EUR/kW (Lovering et al., 2016, Fig. 5, EUR normalized to 2010 value). By contrast, the most recent Western reactor build projects, started in the 2000s and 2010s, have overnight capital costs around $8,000/7,000EUR per installed kW (Buongiorno et al., 2018, p. 36, Fig. 2.3), some of them still subject to ongoing cost increases, and with construction times two to three times as long. Eash-Gates et al. (2020, p. 2350) attribute the observed cost increases to "reactor upscaling, a lack of technology standardization, fragmented industry structure and plant ownership, and increasing plant complexity including increases in the number of plant components, new control systems, redundancy in equipment, and added safety features."

As a result, building new reactors will typically not be part of strategies that conform to QUICK in Western countries, unlike lifetime extensions for existing reactors, which are among the lowest-cost options of avoiding emissions (IEA 2019a). The picture changes when we consider longer time scales.[6] Some have interpreted the rising capital costs of nuclear plants in Western countries in terms of an inherent "negative learning curve," but one can also interpret the historical record as constructive evidence that far lower capital costs and shorter build times than today are feasible, even with 1970s inferior levels of technological development.

In order to bring down construction costs and construction times to 1970s levels (and preferably below), learning effects from serial construction will be indispensable. However, as shown by Eash-Gates et al. (2020), serial construction is not sufficient for cost reductions. In the US, construction costs of repeated designs actually rose more often than they fell (Eash-Gates et al., 2020, pp. 2351–2352). According to these authors, the two most important causes of cost increases are decreasing labor productivity and increasing commodity use. They suggest that pursuing designs that lead to reduced commodity use and the automation of construction processes may be the most promising route toward cost reductions.

There are two views on how economies of scale are to be leveraged to make construction of nuclear reactors as cost-competitive as possible. The first is reflected in the fact that, historically, all nuclear reactor build-out programs moved to ever larger designs, with the EPR currently being the largest reactor in the world, at a capacity of 1.65 GW. The main benefit of larger reactors is that, in terms of installed capacity (in MW), they tend to be cheaper than smaller reactors of similar design. Each new reactor involves an investment at the scale of billions of dollars, however, which means that, unless state-actors provide a secure long-term financing, investors will regard such projects as risky. Adverse experiences with first projects of any given design will lead to even more hesitancy, which will further reduce learning

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[6] See (Jewell & Cherp, 2020, pp. 6–7), for references to conflicting views on suitable speed metrics and conflicting resulting verdicts

opportunities. Experience with cost developments under this strategy is mixed: costs trends rose almost uniformly in the US, but remained largely stable in France (see Grubler (2010) and Escobar-Rangle and Leveque (2015) for nuance) and, more recently, in Japan, China, and South Korea (Buongiorno et al., 2018). Berthélemy and Escobar Rangel (2015) credit design standardization and stable architect-engineer teams with successes in preventing cost escalations and enabling modest temporary cost reductions in the French program.

The second view is that comparatively small "modular" reactors (SMRs) should be constructed at industrial factory-like facilities in large numbers.[7] Historical records of cost development are absent here since SMRs have not been built at any meaningful scale so far. However, observations about granularity provide grounds for optimism (Sweerts et al., 2020; Wilson et al., 2020): energy technologies with smaller unit sizes have a track record of higher learning rates. Learning rates drop by a few percentage points per order of magnitude of the units built and turn negative for units above certain threshold sizes.

SMRs are likely to experience a "valley of death" in that the first units will be more expensive (per unit of capacity) than more traditional large units, and realizing the envisaged economies of scale will require some stamina of investment. For an agent focused on QUICK, such a long-term investment may not seem appealing, compared to investments in mature renewable energy sources, which promise quick and relatively cheap emission reductions, especially at low levels of VRE penetration. By contrast, investment in SMRs will be attractive for actors guided by FACILITATE and ZERO. Purchasing SMRs, if it enables learning effects and allows some designs to overcome the "valley of death", may be a cost-effective step in global emissions reduction, similar to the German feed-in tariffs for solar PV in the 2000s mentioned in Section 3.

A more principled worry is that the operating costs of SMRs may be higher than those of large reactors because of a less favorable staff-to-output ratio. Systematically assessing the potential of SMRs in comparison to larger units is beyond the scope of this paper. We suspect that the question of which option will be more beneficial for which actor will depend on geography, technological advancement, and market design.

4.4 Nuclear Energy in Zero Emissions Energy Systems

Because of their high capital and low operating costs, nuclear reactors are most suited to provide constant electricity at high power output, covering "base-load." Although several modern reactors can be used for load-following (Locatelli et al., 2015, 2018), their economic profile makes them not ideally suited for that role. A middling "flexible base" mode is also possible, however, in which reactors generate maximal output for most of the time but modulate down during periods of high solar and wind production and/or very low demand.

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[7] See Mignacca and Locatelli (2020) for a review of economic perspectives for such small modular reactors (SMRs) and Sovacool and Ramana (2015) for an elaborate pessimistic perspective

Recent modeling (see Jenkins, Luke, and Thernstrom (2018) for a review) of scenarios with different electricity generation mixes concludes that — at close-to-zero emission limits — mixes including at least one “firm” (available with high reliability) low-carbon source tend to be significantly cheaper than those relying exclusively on variable renewables and storage. Notably, this holds for a majority of the 912 scenarios for the Northern and Southern US electricity systems considered by Sepulveda et al. (2018). In the least-cost system, the firm low-carbon source typically runs in the “flexible base” mode. If a zero emissions constraint is imposed, having at least one such firm zero-carbon source reduces costs by 10–62% (see Long et al. (2021) for a more recent effort coming to a similar conclusion for a specific region). Alternatively, if emission limits are imposed by imposing a carbon price, the share of nuclear energy (or some other source with similar economic characteristics) increases, at the expense of unabated fossil fuels and sometimes even variable renewables (Hirth, 2013, 229).

This finding is plausible in the light of real-world examples of low-emission electricity systems (including those of New Zealand, Norway, Sweden, Iceland, Costa Rica, France, and Switzerland), which all rely on a high share of at least one firm low-carbon source: hydroelectric energy, nuclear energy, or geothermal energy.[8] Indeed, in view of the limited geographical availability of hydropower and geothermal energy, nuclear energy is often the most scalable and geographically flexible firm low-carbon source (Buongiorno et al. (2018), NEA (2018), and IEA (2019a)).

There are upper cost thresholds above which nuclear energy no longer figures in least-cost zero-emission systems. In the modeling of Van Zuijlen et al. (2019) for Europe, for instance, this is the case for capital costs of 7900 €/kW and build times of 10 years per reactor. By contrast, if capital costs of 5300 €/kW are achieved and build times below 7 years, nuclear energy contributes “between 30 and 45% of total demand” (van Zuijlen et al., 2019, p. 13) in least-cost scenarios.

Because electricity from existing reactors is generally cheaper than from new reactors, one may think that there is a clearer ethical case for life-time extensions than for new reactor projects. Indeed, from the point of view of QUICK, this is generally true, and, depending on the exact time scale of quick emission reductions considered, building new reactors will tend to be disfavoured compared with expanding renewables. From the perspective of ZERO and FACILITATE, however, the verdict can be the reverse: reactor lifetimes can often not be extended until 2050, when a zero-emission system should be reached, whereas new reactors can contribute to such a system. (The same applies, of course, to wind turbines and solar panels, which have shorter life spans, in the range of 20–30 years, as opposed to 60–80 years for nuclear plants.) From the perspective of ZERO, the main benefit of reactor life-time extensions may well be that, by obviating the temporary need for new fossil fuel plants, they help avoid the lock-in of fossil fuel infrastructure. However, it is only through successful new reactor projects that learning effects can be enabled which are needed for making nuclear-driven decarbonization more economically

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[8] Among these regions, the share of nuclear power in 2019 was highest in France (~72%), followed by Sweden (~40%)

attractive for others. Accordingly, from the perspective of FACILITATE, new reactor projects will often be ethically preferable over life-time extensions, even if the latter have a cost-benefit ratio that is better prima facie. Indirectly, life-time extensions may facilitate new reactor projects by preserving know-how and infrastructure.

Recent modeling by Wealer et al. (2019) suggests that new reactors in Western liberalized electricity markets will not be profitable for the foreseeable future. On the basis of this finding, these authors advise against any role for new nuclear reactor builds in climate change mitigation. However, if we combine this finding with the results reviewed above on least-cost near-zero emissions electricity mixes, the real lesson is different. Markets in which renewables are largely shielded from value deflation and where carbon prices are too low to impose near-zero emission limits, but which are otherwise "liberalized," may not incentivize strategies that are in conformity with ZERO. Moreover, the historical cost records for new nuclear reactors show that capital costs below 3000 $/kW are obtainable. Below this threshold, according to Ingersoll et al. (2020), investments in new reactors become economically attractive even in current liberalized electricity market designs. For actors oriented toward FACILITATE, helping to make such reactors globally available is a natural goal.

Beyond electricity, further potential contributions of nuclear energy to zero emissions energy systems include shipping (Hirdaris et al., 2014), industrial heat (Friedman et al., 2019), and synthetic fuels based on hydrogen. In hydrogen production, nuclear energy's constant production profile is an advantage because it enables high utilization of commodities such as electrolyzers, as well as higher temperatures for more efficient hydrogen production (WNA 2021). However, to make such hydrogen competitive fossil fuel-based hydrogen, both capital costs and commodity costs must be very low (IEA, 2019b).

5 Getting to Zero Emissions: Non-economic Challenges

If SMC holds, economic aspects of nuclear energy are central to whether it will help to decarbonize energy systems. However, deployment of nuclear energy may also affect the feasibility of decarbonization in ways that are not primarily economic.[9]

5.1 Public Opinion

For an energy strategy to be politically feasible, it must not rely on energy sources about which public opinion is extremely negative. By and large, nuclear energy is less popular than renewables (Bergquist et al., 2020), and it is widely regarded as more risky. Where energy strategies relying on nuclear energy are socially infeasible,

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[9] In the literature around nuclear energy and other energy sources, these non-economic considerations are often discussed under "sustainability" (e.g., Verbruggen et al., 2014: JRC 2021). For our purposes, it seems more useful to discuss the different factors separately as they relate to the prospects of decarbonization rather than under that umbrella concept

they will not conform to ZERO after all, even if they would be economically preferable and thus preferable in the light of SMC. Agents responsible for energy system development should in any case try to disseminate state-of-the art information concerning the environmental characteristics of various energy sources, their potential utility for decarbonization, and their actual safety and risk profile (see Section 6.1).

Nuclear energy is not alone in encountering community resistance. Local opposition against wind turbines has significantly slowed down the expansion of wind power in the German Energiewende (see 5.2). In addition, though nuclear energy is less popular than renewables on the political left and among traditional environmentalists, the reverse is often true for political conservatives. Indeed, in some parts of the world nuclear energy has the potential to engage the traditionally "climate-sceptical" political right. Successful bipartisan legislative initiatives in the US to speed up the development of advanced nuclear reactors reflect this.[10] It should also be noted that, even in nuclear-sceptical western countries, the popular acceptance of nuclear energy is highest among those who are living closest to nuclear reactors (Pidgeon et al., 2008).

5.2 Land Use and Power Density

Strategies that rely heavily on renewables face challenges related to land requirements. This is the second important factor, besides intermittency, why including nuclear energy in one's energy strategy can facilitate conformity to ZERO.

If one looks at the global level, the problem seems manageable: human civilization's final energy use per unit of time (i.e., after heat losses) is approaching 15 TW. Since Earth's total land area is around 150 Million square kilometers, this entails an energy demand density of around 0.1 W/m^2. By comparison, according to recent literature, typical average power densities are 1–2.5 W/m^2 for onshore wind, 1–5 W/m^2 for offshore wind, 0.5 W/m^2 for biomass, 3–10 W/m^2 for solar farms (Van Zalk & Behrens, 2018). For comparison, coal, natural gas, and nuclear energy have power densities in the 100s or even 1000s of W/m^2.

A simple calculation based on these numbers shows that, in a global 100% renewables scenario, the total share of land devoted (partially) to energy production would be no more than a few percent, at least with current consumption levels. If offshore wind provides a large share of total generation and solar panels are installed mostly on roofs, the figure may be as low as 1%. Moreover, as pointed out by Jacobson et al. (2018), land use in the strict sense would be far lower still because large parts of the area involved (e.g., space between wind turbines) can be used for other purposes such as agriculture (though reducing the efficiency of these other purposes).

However, this global average hides significant variation in human population densities. On a more fine-grained regional or national level, the power densities of harvested natural energy flows do pose enormous challenges. In densely-populated industrialized countries, the demand densities of total final energy are often

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[10] https://www.epw.senate.gov/public/index.cfm/2019/1/president-trump-signs-bipartisan-nuclear-energy-legislation-into-law

similar to the power densities of renewables. For example, average demand density is roughly 2 W/m^2 in Belgium, and 1 W/m^2 in Germany. This means that, if those countries were to cover their final energy consumption by means of domestic renewables, an area of a similar order of magnitude as the country itself would be required. This condition is of course unnecessarily strict, but it should be noted that imports from neighboring countries may not be very helpful because weather patterns may spread across large geographical areas, which means that peaks and valleys in the generation profile of variable renewables will occur at similar times.

It is useful to inspect a comprehensive "100% renewables" scenario on the level of the whole of Europe, to appreciate the scale. In the one developed by Ram et al. (2019, see Fig. 3.2–3), Europe will generate about 6000 TWh of onshore wind power by 2050 annually, which translates into an area of 240,000–600,000 km^2, taking into account inter-turbine spacing (for comparison, Germany's land area is 357 000 km^2). The area requirements of the envisaged 11,000 TWh generated by solar PV would further increase pressure on land availability. Long-distance transmission lines can mitigate the intermittency challenge, but they make the energy system even more land-intensive. As for hydrogen production and associated synthetic fuels, there may simply not be enough land available in Europe (Belmans et al., 2020), which means that hydrogen will have to be mostly produced in less densely populated regions with larger wind and solar resources, and then be imported from there. However, transformation and transportation losses will occur (see 4.2.), and it is unclear at present whether such emission-free fuels can be made available at costs similar to fossil fuels.

Germany, a global leader in renewables deployment, currently generates around annually 125 TWh from wind (onshore and offshore) and 50 TWh from solar power (Burger, 2020), which adds up to about 7% of its final energy use of 2500 TWh (IEA, 2020, p. 23, Fig. 2.7). Even in this early stage the country has more than 1000 local anti-wind initiatives, which in 2019 severely slowed down wind turbine additions (DW, 2019). Efficiency gains may reduce area availability challenges, but it is doubtful whether countries with similar power demand densities can decarbonize without relying heavily on imports, and any strategy that relies on imports does not conform to ZERO as long as emission-free energy is globally scarce.

Finally, where demand density is high, the area requirements of variable renewables may exert upward pressure on land prices at advanced stages of decarbonization. This factor will have to be taken into account in assessing whether a 100% renewables-based energy system can be economically competitive with one that relies on fossil fuels. Cost escalations arising from area scarcity, just as those arising from intermittency, can be avoided by including nuclear energy or another firm low-carbon source with high power density in one's energy strategy.

5.3 Material Reserves Depletion

Both renewables and nuclear energy have material requirements that are associated with depletion risks. Giurco et al. (2019) provide an up-to-date review with respect to renewables and NEA (2020) for uranium reserves. For both types of sources, the upshot is that material depletion is unlikely to be a limiting factor in upscaling these technologies in the next decade. For nuclear energy, known uranium reserves suffice for some decades even if light water reactor technology that requires enriched uranium gets somewhat more widely used. A closed-fuel cycle as used in France reduces materials and environmental footprint further (Poinssot et al., 2014).[11] If nuclear energy use grows by an order of magnitude or more, some combination of expanding mining, extracting uranium from seawater, higher-efficiency use and recycling of spent uranium fuel in breeder reactors, as well as the use of thorium as fuel, will be necessary. Extracting uranium from seawater would provide fuel for several centuries (Lightfoot et al. 2006). Finally, we note that the mining activities needed for enabling global expansion of renewables may aggravate threats to biodiversity (Sonter et al., 2020). According to the IEA (2021), the overall need for critical minerals for the energy transition will need to increase around six-fold by 2040, which is mainly driven by increased battery storage, transmission, and renewables installations. Due to the high energy density of uranium, nuclear energy requires comparatively little mining and may thus help mitigate these threats. Energy strategies diversify risks from material reserves depletion if they include significant contributions from a variety of energy sources.

6 Interim Conclusion: Ethics of Nuclear Energy in the Light of Climate Change

Our conclusions from Section 4 and Section 5, based on the empirical evidence reviewed there and the assumption SMC, are the following:

Inclusion of nuclear energy in one's energy strategy can be expected to facilitate decarbonization, with the possible exception of countries where either (i) another firm low-carbon resource is available in geographic abundance, (ii) public opposition is very strong and opportunities for bipartisan cooperation low, or (iii) the current level of economic and scientific development makes the feasibility of a nuclear energy program doubtful. For all other countries, we conclude that — from the point of view of ZERO, assuming SMC and bracketing all considerations about health, safety, and proliferation (see below) — inclusion of nuclear energy in their energy strategy is plausibly ethically mandated. The considerations reviewed here are too general to form the basis of concrete policy recommendations, but we suggest that investing in nuclear energy at the same order of magnitude as investing in renewables would be a reasonable guideline (again, from the point of view of ZERO), especially for countries that already generate substantial amounts of nuclear energy (e.g., France, USA, UK, Sweden, China).[12] For countries where public resistance

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[11] However, setting up a closed fuel cycle may increase costs for the foreseeable future. Moreover, the closed fuel-cycle as practiced in France, when extended to newcomer countries, may increase proliferation risks, see Section 7.2

[12] We did not explicitly discuss a 100% nuclear/0% renewables strategy as envisaged by Brook et al. (2018). We believe that there is no reason for having a high degree of confidence that such a strategy will have low economic costs and high public support and, therefore, do not expect it to conform to ZERO

to nuclear energy is much stronger than to other energy sources (condition (ii)), the most ethical course of action may be to refrain from deployment for the time being, while transparently communicating with the public about the benefits and downsides of various energy options, with an eye toward opening up possibilities for future investment.

The ethical assessment of nuclear energy use from the point of view of FACILITATE depends on an agent's prospects for using nuclear energy investments to gain "leverage" in terms of bringing down emissions elsewhere. Those prospects will be highest for agents that have the economic and scientific capabilities to potentially facilitate decarbonization in other countries. In particular, for actors who have a strong nuclear industry and technological-scientific infrastructure (in the Western world: France, Canada, and the USA), investments in new nuclear reactors, as well as assistance to other countries interested in developing a civilian nuclear program, will be ethically mandated by FACILITATE. For actors who have no such strong nuclear infrastructure, but instead have a strong infrastructure in other low-carbon energy generation technology (for instance, Denmark in wind energy), there may not be a strong ethical case for investment in nuclear energy by the standards of FACILITATE. For developing countries, the prospects for facilitating decarbonization elsewhere may be comparatively lower, whether through nuclear energy or by other means. Finally, it should be pointed out that, for developed and developing countries alike, the prospects for facilitating decarbonization by investing in some low-carbon energy source depend largely on which, and how many, *other* actors are already pursuing it.

7 Sensitivity Analysis

The ethical assessment of specific instances of nuclear energy use can be influenced by considerations beyond climate change mitigation. Here we ask whether such considerations might be "crucial" in the sense of Bostrom (2014), which means that it "might possibly reveal the need not just for some minor course adjustment in our practical endeavors, but a major change of direction or priority." We consider health and safety aspects of nuclear energy use beyond climate change (Section 7.1) and effects from the possible interaction with nuclear weapons proliferation (Section 7.2).

7.1 Health and Safety Aspects

Many people believe that, even if nuclear energy has benefits for climate change mitigation, its use is unethical in view of its health and safety risks. The report by the German ethics commission on nuclear energy reflects this belief when stating that "almost all scientific studies come to the conclusion that renewables and the improvement of energy efficiency entail lower health and environmental risks than nuclear energy" (Ethik-Kommission, 2011, p. 33-34). The report even compares nuclear energy unfavorably with fossil fuels in these respects. Remarkably, no studies are cited in that passage.

In fact, systematic comparisons between different energy sources over their entire life cycle show that, even when taking into account the accidents at Chernobyl and Fukushima, nuclear energy is among the least health-damaging of all major energy sources, on a range of different indicators (Kearns et al., 2012; Markandya & Wilkinson, 2007; Sovacool et al., 2016). Of course, overall safety comparisons are crude in that they do not distinguish between different versions of energy sources (e.g., technology "generations") and application contexts (e.g., safety culture). But the clear overall picture emerging from these studies, contrary to the puzzling claims of the "Ethikkommission," is that nuclear energy is comparable to modern renewables in terms of health and safety and far superior to fossil fuel-based energy sources. This picture is confirmed by a recent report of the European Commission Joint Research Centre (2021), which finds that, to the degree that renewables conform to the "do no significant harm" criteria of the EU sustainable finance taxonomy, nuclear energy does so as well.

Nuclear waste — notably high-level waste, which mostly consists of spent fuel — is sometimes cited as a health concern. Geological disposal is considered the default option for dispensing with spent fuel. Where it is used, the impact on the health and safety of future generations can be expected to be negligible compared to the beneficial effects due to avoided greenhouse gas emissions.[13] Geological disposal is already used for dispensing with other forms of hazardous waste that create health risks indefinitely, at scales far larger than envisaged for nuclear waste disposal.[14] As for high-level nuclear waste, according to the United States's EPA standards for suitable geological repository, effective radiation doses resulting from leakages may not exceed 0.15 MilliSievert per year for the first 10,000 years and 1 MilliSievert for the first 1 Million years, even in high-exposure scenarios and even for people living directly above the repository sites. These thresholds are significantly below natural background radiation levels in most regions. An independently audited study for the Finnish high-level repository (Hjerpe et al., 2011) concludes that exposure levels even in worst-case leakages do not reach the order of magnitude of background radiation.[15]

From an ethical perspective, scenarios of nuclear accidents or waste depository leak scenarios can certainly play a role in determining suitable locations for siting of reactors and repositories. But, generally speaking, the scale of harm to be expected from repository leakages, and even future accidents (which no doubt will occur if

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[13] Potentially replacing geological disposal with a different method, potentially as part of using a different fuel cycle, interacts with the sustainability and proliferation questions, and assessing these interactions from an ethical point of view is beyond the scope of this paper, see Taebi (2011) for a thorough assessment

[14] See the EPAs overview "Class I Industrial and Municipal Waste Disposal Wells," bit.ly/32qJgsk

[15] In any event, additional radioactive waste is a case of "diminishing marginal costs." Either we already have a good solution for radioactive waste and it will work for radioactive waste yet to be produced; or we have no solution, and in that case we will have to invest in such a solution even if we decide to completely phase out nuclear energy

the industry is scaled up) is plausibly many orders of magnitude smaller than the harm at stake in climate change and no larger than the expected harm from alternative energy sources. We conclude that health and safety considerations are not "crucial" in Bostrom's sense for the technology's ethical assessment.

At this point, it is worthwhile to recall that, by SMC, nuclear energy must be cheap to have large climate change mitigation benefits. If regulations about nuclear waste disposal make nuclear energy safer but also more expensive, the net expected benefit of such regulations for human health and the environment will often be negative. Similar considerations apply to regulations regarding the licensing of new reactor models and regarding emergency plans for accidents. According to Waddington et al. (2017), except for some evacuations immediately after the Chernobyl disaster, evacuations following nuclear accidents uniformly had large *negative* net effects on human health. As a topic for future research, we flag the question of whether the same might hold for regulations on new reactor licensing and waste disposal and what this means for the ethical assessment of such regulations, especially from a utilitarian perspective.

7.2 Proliferation of Nuclear Weapons

Nuclear war is one of the most serious global risks for both current and future generations, rivaling, potentially surpassing, climate change in terms of expected damage (Ord, 2020).[16] Civilian nuclear energy use can interact with the proliferation of nuclear weapons, which is one of the most important factors driving the risk of nuclear war. If nuclear energy use can in this way indirectly influence whether or not some nuclear war will occur, it may thereby have consequences for humans and ecosystems worldwide on a scale comparable to what is at stake in climate change mitigation.

In what follows we argue that an expansion of nuclear energy, depending on where and how it is carried out, can either increase the risk of weapons proliferation, be neutral with respect to that risk, or reduce it.

For an agent intending to build nuclear weapons, civilian nuclear energy infrastructure can help to acquire fissile, bomb-grade, material. Candidate materials include uranium-235 and plutonium-239. The options are to either increase the proportion of uranium-235, which comprises only 0.72% of natural uranium, to at least 60%, or to transform uranium-238 into plutonium-239. One cheap option, open to countries even without any civilian nuclear energy program, is to build a graphite-moderated reactor specifically designed for plutonium production. However, the front- and back-end infrastructure of the civilian nuclear fuel cycle can also be misused to accomplish this. The globally most widely used reactor types — light water reactors — require low-enriched uranium (uranium-235 concentration of around

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[16] This seems to be the default view. It is conceivable that proliferation has an opposite, beneficial, effect via deterrence, namely, lowering the probability of war so much that the global expected damage associated with war decreases through it. Assessing this debate on "nuclear peace" is beyond the scope of this paper

3–5%), and the facilities for producing this can also be co-opted to produce high-enriched uranium suitable for weapons. In addition, reprocessing facilities that recycle part of the spent nuclear fuel can be used to separate out plutonium for creating a nuclear bomb.

Indeed, India and Pakistan used reprocessing facilities provided in the context of foreign assistance to create weapons fuel. Such "nuclear assistance" also helped South Africa, Israel, and North Korea with their weapons programs (Fuhrmann, 2009, 15-23). Kroenig (2010) provides extensive documentation of how, notably, "sensitive" nuclear assistance — e.g., supply of uranium enrichment and plutonium reprocessing facilities — has made it more likely that the recipient countries will develop nuclear weapons. Moreover, according to Fuhrmann (2009) and many contributors to (Stulberg & Fuhrmann, 2013), even non-sensitive nuclear assistance can contribute to proliferation, but see (Bell, 2016; Montgomery, 2013) for different views.

These observations are especially worrying for actors who are motivated by FACILITATE: making decarbonization economically attractive for as many other international actors as possible. In order to fulfill FACILITATE, nuclear investment will reasonably have to be combined with openness to deliver civilian nuclear assistance, although with factory-made SMRs this could be mitigated.

On the other hand, as documented by Gibbons (2020), the US has repeatedly used nuclear assistance — and in some cases merely offers of nuclear assistance — as a bargaining tool to entice other countries to join non-proliferation agreements, notably the IEAE's Model Additional Protocol. Under this protocol international inspectors gain far broader access to a country's civilian nuclear facilities than under the regulations of the Non-Proliferation Treaty (NPT).[17] Such bargaining may be the reason for the surprising finding by Miller (2017, 2018) that, overall, having a civilian nuclear energy program does not increase a country's propensity to proliferate. The most ambitious agreement that resulted from US bargaining is the US-UAE 123 Agreement (referring to Section 123 of the 1954 US Atomic Energy Act), also referred to as the non-proliferation "Gold Standard" (United States State Department Bureau of Public Affairs, 2009). In this agreement, the United Arab Emirates obtained a guarantee for extensive US nuclear assistance in exchange for a commitment not to acquire enrichment and reprocessing facilities. Evidently, having a competitive civilian nuclear industry is a precondition for using nuclear assistance as a bargaining chip along these lines. In light of the decline of the US nuclear industry's competitiveness, Gibbons therefore recommends:

> The positive effects of nuclear assistance on nonproliferation suggest a second important policy lesson for the United States and its allies: attempt to regain and maintain a competitive nuclear industry. When US and allied technology is desirable, the nonproliferation regime benefits. Indonesia, Japan, Egypt, and several other states joined the NPT in part to receive nuclear technology from Western suppliers. Today, Egypt is purchasing its nuclear technology from

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[17] All countries except India, Pakistan, Israel, South Sudan, and North Korea are members of this treaty

> Russia and China and has not agreed to the most stringent IAEA safeguards agreement, the Additional Protocol. If suppliers less concerned with nonproliferation [i.e. China] have better technology or offer more favorable agreements than the United States and its allies, the nuclear nonproliferation regime could be weakened. (Gibbons, 2020, p. 294)

More generally, if a proliferation-concerned actor strengthens her own nuclear industry or that of like-minded allies through purchase of (comparatively) proliferation-resistant products[18], she may thereby reduce overall global proliferation risks.

In sum, there is reason to believe that considerations about nuclear weapons proliferation have the potential to be “crucial” for the ethical assessment of nuclear energy in Bostrom’s sense, though in two countervailing ways: when it weakens the non-proliferation regime, for instance by the spread of enrichment facilities, they can render nuclear energy use unethical even if it would otherwise have been ethical; alternatively, when it helps strengthen the proliferation regime, for instance by providing incentives to join non-proliferation agreements beyond the NPT, they can render nuclear energy use ethical *even if* an ethical case for it would otherwise have been lacking.

8 Conclusion

We have argued for two central claims: first, under plausible empirical assumptions and ethical criteria, multiple countries currently face an ethical obligation to invest in nuclear energy to mitigate climate change; second, the overall ethical verdict on nuclear energy investments may differ from the climate-related verdict, depending on how it interacts with nuclear weapons proliferation. That overall verdict, however, is unlikely to be affected by considerations related to health and safety aspects.

Our analysis is based on a number of empirical assumptions that can be interpreted differently and/or whose evidence base may change. Notably, it may turn out that some affluent countries will happily agree to significant reductions in welfare for the sake of unilateral decarbonization, thereby falsifying or at least reducing the scope of SMC; new experiences and insights into the economic and technical feasibility of low-carbon energy systems may lead to a revised assessment of whether 100% renewables scenarios are likely feasible; development of new technologies for climate change mitigation may reduce or enhance the usefulness of nuclear energy; and a better understanding of the historical interplay between nuclear energy use and proliferation may influence the prospects for shaping that interplay in the future.

In any event, to avert dangerous levels of global warming, global emissions of greenhouse gases must be curtailed and eventually brought down to zero as quickly as possible. Given nuclear energy’s potential to facilitate deep decarbonization, and

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[18] Proliferation-resistance depends, for instance, on the fuel cycle. While, as of today, “no “silver bullet” fuel cycle has been found that will permit the relaxation of current international safeguards or national physical security protection levels” (Bathke et al. 2012), some fuel cycles are easier to safeguard than others

thus to reduce the tail risk of catastrophic climate change, our interim conclusion remains unscathed for a variety of countries and for the time being: from an ethical point of view, they must invest in nuclear energy.

Acknowledgements We would like to thank Michael Aird, Ronnie Belmans, Sam Bliss, Kirsty Gogan, Lars Roobol, Jonathan Symons, Matthias Vanderhaegen, and three anonymous reviewers of *Philosophy and Technology* for comments and/or feedback on previous versions of this paper.

Author Contributions The authors jointly designed and wrote the paper and approved the final manuscript.

Availability of Data and Materials Not applicable.

Code Availability Not applicable

Declarations

Conflicts of Interest The authors declare no competing interests.

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